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Evaluation of Thermal Diffusivity of the Quaternary Deposits Based on Laboratory Analysis of Samples Taken by Geotechnical Drilling

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Abstract

This paper present a model for calculating the thermal diffusivity of a crust sedimentary deposit, where it is treated as a porous medium saturated with fluid. In the model a range of petrophysical characteristics of the layers are used. Properties were obtained by analyzing, in an authorized laboratory, the cores taken by geotechnical drilling, from the layers investigated. Three models were selected to assess the equivalent thermal conductivity of the fluid-saturated porous medium (weighted geometric mean, Beck based on a modified Maxwell model, Krupiczka). Equivalent volumetric heat capacity of a fluid-saturate, porous medium is calculated as a weighted average of volumetric heat capacity of the components.The proposed model has been used in case studies for calculation of thermal diffusivity of the crust layer, within a region from Romania. Obviously, geophysical exploration data are needed when appropriate however. If that exploration is not possible, then the results of the thermal diffusivity of the crust layers, presented in the paper, may constitute benchmark elements for similar studies which require such knowledge.

Key words: *Layers of the Earth's crust, Thermal diffusivity, Petrophysical measurements.*

Model for Calculating the Thermal Diffusivity

To assess the thermal diffusivity of the crust layer, a model is proposed, in which the petrophysical and thermal properties of the lithological entities must be known. The thermal diffusivity gives an indication of the thermal inertia of bodies namely, how it is higher, the body is heated or cooled faster. It is believed that the crust layer comprises solid and fluid which is a porous medium saturated with fluid.

Permanently in the conduction regime, a fluid-saturated porous medium - can be treated as a continuous medium equivalent, to which it is defined the equivalent thermal conductivity, equivalent volumetric heat capacity and thermal diffusivity. Thermal diffusivity is defined by the relationship [4, 7].

$$a = \frac{\lambda}{C} \tag{1}$$

In the case of a equivalent continuous medium, it is defined the thermal conductivity tensor. The tensor components value depends on the own conductivity of each phase, saturation, porosity, heat flow direction, state of thermodynamic parameters (pressure, temperature). If it is assumed that the fluid-saturated porous medium is isotropic thermal, the thermal conductivity tensor is spherical and can be defined by the equivalent thermal conductivity scalar.

The determination of the value of conductive heat transport size gives the best results if it is based on experimental data of each case study. There are methods of calculation based on idealized models (series, parallel, weighted geometric mean, Beck based on a modified Maxwell model, Vries, Woodside and Messmer , Krupiczka) where are used the appropriate physical properties [2, 3, 4, 6, 8, 10]. Three models were selected to assess the equivalent thermal conductivity of the fluid-saturated porous medium [2, 3, 4, 6, 8].

Option I, the weighted geometric mean model is the most used, because it is simple and easy to apply and has no restriction on the values of intervening in the calculations.

$$\lambda = \lambda_F^{\Phi} \cdot \lambda_S^{1-\Phi} \tag{2}$$

Option II, Beck model is a modified Maxwell model, which, in the opinion of the proposal, leads to good results if the porous medium has features $\Phi < 0.5$ and $\frac{\lambda_S}{\lambda_F} \in (1...300)$:

$$\lambda = \lambda_S \left[\frac{\left(2\frac{\lambda_S}{\lambda_F} + 1\right) - 2\Phi\left(\frac{\lambda_S}{\lambda_F} - 1\right)}{\left(2\frac{\lambda_S}{\lambda_F} + 1\right) + \Phi\left(\frac{\lambda_S}{\lambda_F} - 1\right)} \right] \tag{3}$$

Option III, Krupiczka model proposes a relationship of the form:

$$\lambda = \lambda_F \left(\frac{\lambda_S}{\lambda_F}\right)^{A + B \log\frac{\lambda_S}{\lambda_F}} \tag{4}$$

in which:

$$A = 0.280 - 0.757 \log \Phi \text{ and } B = -0.057 \tag{5}$$

The author of this relationship says that the porous medium must have the porosity $0.215 < \Phi < 0.476$. It also states that testing 165 data from the specific publications, it was found that at 76 % of them , the difference between experimental and calculated values obtained with equation (4) is $\pm 30\%$.

The thermal conductivity of the solid, λ_S, is calculated as a weighted average according to its volumetric composition and thermal conductivities of the components:

$$\lambda_S = \sum_{i=1}^{4} r_i \lambda_{S,i} = r_1 \lambda_1 + r_2 \lambda_2 + r_3 \lambda_3 + r_4 \lambda_4 \tag{6}$$

It was considered that the fluid-saturated porous medium has as a solid medium a rock of a certain composition. As a result, in the relation 3, the notation of the solid constituents refers to : 1 – clay; 2 - powder ; 3 - sand ; 4 - gravel.

It was found that the fluid medium, that saturates the pores of the solid medium, is composed of water and air. As a result, the saturation equation may be written:

$$S_{aer} + S_{apa} = 1 \tag{7}$$

The thermal conductivity of the fluid λ_F, is calculated as a weighted average, based on the thermal conductivity of the fluid components and their saturation:

$$\lambda_F = S_{aer}\lambda_{aer} + S_{apa}\lambda_{apa} \tag{8}$$

Assuming that phase changes no occuring, equivalent volumetric heat capacity of a fluid-saturated, porous medium is calculated as a weighted average of volumetric heat capacity of the components, according to the relation [3], [4]:

$$C = (1 - \Phi)C_S + \Phi C_F \tag{9}$$

The volumetric heat capacity of the solid, C_S, is calculated as a weighted average based on its volumetric composition and volumetric heat capacities of the components.

$$C_S = \sum_{i=1}^{4} r_i\, C_{S,i} = r_1 C_1 + r_2 C_2 + r_3 C_3 + r_4 C_4 \tag{10}$$

Volumetric heat capacity of the fluid, C_F, is calculated as a weighted average, based on the volumetric heat capacities of the fluid components and their saturation:

$$C_F = S_{aer} C_{aer} + S_{apa} C_{apa} \tag{11}$$

Experimental Part

Petrophysical properties of the fluid-saturated porous medium (the nature of solid and fluid components, the volumetric composition of the solids, porosity, fluid saturation), which are required in the relations (2) ... (11), are obtained from measurements carried out in a authorized laboratory. The samples were subjected to laboratory analysis and were taken by geotechnical drillings in superficial sedimentary deposits, aluvial tipe, under study [9].

The area investigated in this paper is located in the Romanian Plain. Geotechnical drillings were performed with mechanical drills GTR 790 RHB. Applying the proposed model, based on "in-situ" data, requires experimental research that has significant costs, require time spent in organizing and carrying out the work, special machines and authorized equipment and are carried out by qualified personnel.

We have taken samples of each layer and laboratory analysis carried out in order to know their petrophysical properties. From experimental data held were selected and presented those related to the two geotechnical explorations and 4 cases studies.

Tables 1 and 2 contain characterizations of layers, corresponding to the two geotechnical explorations, denoted by F1D and F2D. Thermal diffusivity was measured for the horizon located at depths of 0.6 m to about 2.4 ... 3.4 m. The first layer that is located at 0 - 0.6 m, which corresponds to plant soil , or the 0.2 - 0.6 m, concerning the horizon transition were not analyzed because when industrial works take place these layers are stripped. Layers located deeper than about 3.4 m were not studied, but the assumption that it is necessary to assess the thermal diffusivity can be applied, using appropriated data, the model presented in this paper. Particle size of solid components of the composition is: 1 – clay with 0.005; 2 - silt with 0.005 ... 0.05; 3 - sand with 0.05 ... 2; 4 - gravel in the grain is greater than 2. The proposed model can be applied to layers of depths as great if there is adequate geotechnical study.

Table 3 presents the results of laboratory measurements on samples from geotechnical drilling exploration. Two layers were studied from each drilling and were noted F11D and F12D, which came from the drilling F1D, respectively F21D and F22D, those from of the drilling F2D.

Table 1. Characteristics of layers – Exploration drill F1D

Depth, m	Rating
0.00 – 0.20	Topsoil
0.20 – 0.60	Transition horizon
0.60 – 2.30	Siltic clay
2.30 – 3.40	Clayish sand
3.40 – 6.00	Sand

Table 2. Characteristics of layers – Exploration drill F2D

Depth, m	Rating
0.00 – 0.20	Topsoil
0.20 – 0.60	Transition horizon
0.60 – 2.00	Clay
2.00 – 3.10	Siltic clay
3.10 – 6.00	Gravel

Table 3. Results of laboratory measurements on samples taken from geotechnical drills

Name	F11D	F12D	F21D	F22D
Lithology	Siltic clay	Clayish sand	Clay	Siltic clay
Horizon, m	0.60 – 2.30	2.30 – 3.40	0.60 – 2.00	2.00 – 3.10
Natural moisture, %	20.51	15.82	18.72	20.45
Porosity, ϕ, %	44.13	30.72	40.08	39.82
r_1 - volumetric fraction of solid component 1, %	40.4	28.1	47	30.6
r_2 - volumetric fraction of solid component 2, %	47.6	27.3	41.2	37.4
r_3 - volumetric fraction of solid component 3, %	10.8	44.4	9	31.2
r_4 -volumetric fraction of solid component 4, %	1.2	0.2	2.8	0.8
Humidity, S_{apa}	0.71	0.93	0.76	0.83

Results and Discussions

After analyzing, selecting and interpreting the laboratory results and the knowledge of studied layer characteristics, it was applied the computational model designed to know the thermal diffusivity of the crust layer. In order to assess the equivalent thermal conductivity of a layer were performed calculations using the three models showed in the relations (2), (3) and (4). In order to calculate the thermal conductivity of the components, that make the fluid-saturated porous medium, the equations (6) and (8) have been applied, in which were used the specific data from the specialized publications [1], [4], [7]. The results obtained are shown in Table 4.

From table 4 it is observed that, in each case studied, the results for the equivalent thermal conductivity of a layer, when applied to a weighted geometric average model are lower than those in the case of applying the pattern model Beck (Maxwell model modified), and greater that achieved using the model Krupiczka.

$$\lambda_{III} < \lambda_I < \lambda_{II} \tag{12}$$

Table 4. Thermal conductivity assessment for layers of geotechnical drills

Thermal conductivity, λ, [W/mK]	**F11D**	**F12D**	**F21D**	**F22D**
Solid, λ_S	2	2.042	1.979	2.023
Fluid, λ_F	0.416	0.537	0.443	0.4815
Option I, the weighted geometric mean model, sample, λ_I	1	1.355	1.086	1.142
Option II, Beck model (a modified Maxwell model), sample, λ_{II}	1.18	1.4848	1.2504	1.298
Option III, Krupiczka model, sample, λ_{III}	0.927	1.254	0.9995	1.024

Table 5 presents the results of calculations performed by applying relations (9) ... (11) , to assess the volumetric heat capacity of solids and fluids that make the layer investigated , as well as for that sample.

Table 5. Volumetric heat capacity assessment for layers of geotechnical drills

Volumetric heat capacity, C, [J/m^3 K]	**F11D**	**F12D**	**F21D**	**F22D**
Solid, $C_S \cdot 10^{-3}$	1869	1763	1892	1783
Fluid, $C_F \cdot 10^{-3}$	2982	3906	3192	3486
Sample, $C \cdot 10^{-3}$	2360	2412	2413	2698

Thermal diffusivity is directly proportional to the equivalent thermal conductivity of the geologic strata and inversely proportional to the equivalent volumetric heat capacity.

Thermal diffusivity was calculated using equation (1) in three versions, corresponding to the three models used to find the equivalent thermal conductivity. The results obtained are shown in Table 6.

Table 6. Thermal diffusivity assessment for layers of geotechnical drills

Thermal diffusivity, a, [m^2/s]	**F11D**	**F12D**	**F21D**	**F22D**
Option I, $a_I \cdot 10^6$	0.4237	0.5618	0.4501	0.4233
Option II, $a_{II} \cdot 10^6$	0.5	0.6156	0.5182	0.4811
Option III, $a_{III} \cdot 10^6$	0.3928	0.5199	0.4142	0.3795

It is noted that, in all cases, it respects the relation:

$$a_{III} < a_I < a_{II} \tag{13}$$

Thermal diffusivity values obtained were compared to the relatively similar data, available in specific publications [1], [4], [7]. The comparison resulted in acceptable consistency. It is emphasized again that in the research carried out, each layer has its own characteristics and were analyzed "in- situ" samples.

The thermal properties depend on each case as a ground layer is characterized by uniqueness. Also, even in a layer under review, in fact, identical properties are not as a whole. Some of the factors on which the thermal diffusivity of the layer to be analyzed is listed the nature of each component , the composition of the solid and the fluid and porosity . It follows that, for each layer should be studied and evaluated the appropriated thermal properties, with samples taken "in-situ" and analyzed in authorized aboratory. Assuming that this thing cannot be done, the data provided in this paper are expected to be a useful reference.

Equation (13) shows that the use of the weighted geometric average model for evaluating the equivalent thermal conductivity leads to thermal diffusivity values ranging from those obtained when the Beck model is applied (Maxwell), to respectively Krupiczka, which justifies its frequent use.

Conclusions

For the calculation model proposed in this paper to evaluate the thermal diffusivity of the crust layer, are used "in-situ" data samples.

The set of geological data, obtained by exploring the lithological entities, necessary when applying the proposed model, is still required to know for a location where are located civil and industrial building shall or where are applicable methods of deposits exploitation for useful substances.

Thermal diffusivity is directly proportional to the equivalent thermal conductivity of the geologic strata and inversely proportional to the equivalent volumetric heat capacity.

A layer of earth's crust is a porous medium saturated with fluid, heterogeneous, characterized by equivalent thermal conductivity and equivalent volumetric heat capacity whose values depend on many factors: the nature and composition of solids and fluids that make it up, porosity, saturation fluids.
Each layer has its specific values for equivalent thermal conductivity and equivalent volumetric heat capacity, respectively the thermal diffusivity and the properties on which their evaluation is carried out to be measured with samples "in -situ" and analyzed in authorized laboratory.

Comparison of thermal diffusivity values obtained in this research, with relatively similar data available in specific publications, taking into account the many factors that influence this technical property, led to acceptable consistency.

The study presented in this paper can be extended to any layer of the earth's crust, where there is adequate geotechnical study, samples taken from each layer and laboratory analysis to determine the petrophysical properties.

Results of thermal diffusivity of the crust layers presented in the paper may constitute elements benchmark for similar studies, where it is necessary to know the thermal properties.

Nomenclature

a - Thermal diffusivity, [m^2/s]
A - Coefficient
B - Coefficient
C - Volumetric heat capacity, [J/m^3 K]
S - Saturation
λ -Thermal conductivity, [W/mK]
Φ - Porosity

Subscript

aer – Air

apa -Water
F - Fluid
i - Index
S - Solid

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Evaluarea difuzivității termice a unor depozite cuaternare pe baza analizelor de laborator ale probelor prelevate prin foraj geotehnic

Rezumat

Această lucrare prezintă un model privind calculul difuzivității termice a unui depozit sedimentar al crustei terestre, în cazul în care acesta este asimilat unui mediu poros saturat cu fluide. În cadrul modelului sunt utilizate o serie de caracteristici petrofizice ale straturilor. Proprietățile au fost obținute prin analizarea, într-un laborator autorizat, a carotelor, prelevate prin foraj geotehnic, din straturile cercetate. Au fost selectate trei modele pentru a estima conductivitatea termică echivalentă a mediului poros saturat cu fluide (medie geometrică ponderată, Beck bazat pe modelul Maxwell modificat, Krupiczka). Capacitatea calorică volumetrică echivalentă a mediului poros, saturat cu fluide, este calculată ca o medie a capacitătilor calorice volumetrice ale componentilor. Modelul propus a fost utilizat în studii de caz destinate calculului difuzivității termice a unor straturi ale crustei terestre, dintr-o zonă din România. Desigur ca sunt necesare datele care se obtin prin explorare geofizică. Daca această explorare nu este posibilă, atunci rezultatele privind difuzivitatea termică a straturilor crustei, prezentate in această lucrare, pot constitui o bază de date pentru studii similare.